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BIM-based automated design for HVAC system of office buildings—An experimental study

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Abstract

Although computer technologies have greatly advanced in recent years and help engineers improve work efficiency, the heating, ventilation, and air conditioning (HVAC) design process is still very time-consuming. In this paper, we propose a conceptual framework for automating the entire design process to replace current human-based HVAC design procedures. This framework includes the following automated processes: building information modeling (BIM) simplification, building energy modeling (BEM) generation & load calculation, HVAC system topology generation & equipment sizing, and system diagram generation. In this study, we analyze the importance of each process and possible ways to implement them using software. Then, we use a case study to test the automated design procedure and illustrate the feasibility of the new automated design approach. The purpose of this study is to simplify the steps in the traditional rule-based HVAC system design process by introducing artificial intelligence (AI) technology based on the traditional computer-aided design (CAD) process. Experimental results show that the automatic processes are feasible, compared with the traditional design process can effectively shorten the design time from 23.37 working hours to nearly 1 hour, and improve the efficiency.

Keywords
BIM;
BEM;
HVAC system;
automated design

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1 Introduction

HVAC systems provide a desirable indoor environment and are an essential element in almost all buildings. Residential buildings are often equipped with air conditioner packages that are standardized and can be directly produced from factories. However, the heating, ventilation, and air conditioning (HVAC) systems of large commercial or office buildings are typically built-up systems that require design and are significantly more complicated than standardized air conditioner units. A flow chart of the typical process of HVAC design is provided in Figure 1, showing the process from obtaining the project information to generating the HVAC design results. For each project, engineers must perform substantial amounts of tedious work, such as arranging duct layouts and sizing the system because every building is unique. Additionally, the engineer's design process is sequential. Any modification to previous steps affects all the subsequent design results, which leads to the repetition of design work. There have been many studies on automated architectural, engineering, and construction (AEC) design processes that provide efficient and convenient technical means for HVAC system design. On this basis, adding artificial intelligence (AI) technology can make the traditional design process more streamlined and reduce engineers' repetitive work.

In this paper, we propose a technical framework for automated HVAC system design. The framework splits and simplifies the traditional complex HVAC system design process, and can initially realize the automated calculation, design and result generation of simple office buildings based on the existing technical methods. At the same time, this study verified the feasibility of the automatic design process through an experimental study of the automated HVAC system design process for a specific office building. Compared with the traditional design process, the design process proposed in this paper can greatly reduce the repeated work of designers, shorten the design time, and improve the design efficiency.

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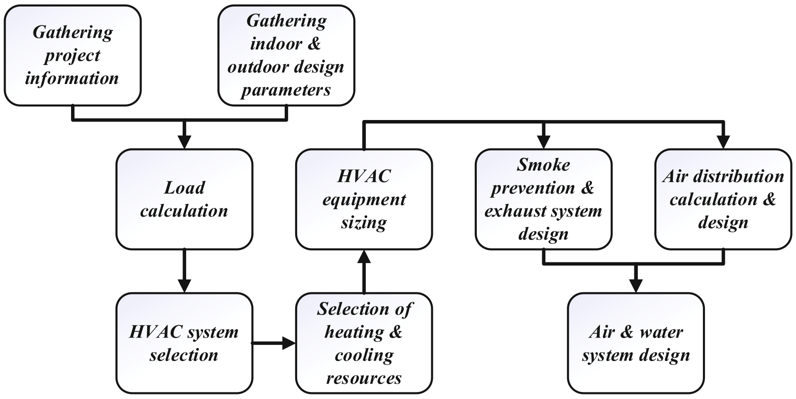


Fig. 1 Typical workflow of HVAC system design

It is of great significance to improve the digital and intelligent level of HVAC system design.

This paper aims to explore feasible algorithms for automated HVAC design and demonstrates the automated design process through an experimental study. The contents of this paper are as follows. Section 2 contains an overview of the literature on design automation in the AEC area as well as the current state of BIM-based HVAC design. Section 3 introduces a framework for automated HVAC design and elaborates upon the methodology of each part of the framework. Section 4 presents an experimental study for the automated HVAC design process of an example office building and Section 5 presents this discussion of the experiment research. Section 6 presents this study's conclusions and the future direction of the research in automated HVAC design research.

2 Literature review

Design automation is an important research area in the AEC domain, having the potential to significantly reduce time, cost, and other design and human resources involved in a project's life cycle (Kasmarik 2010). One of the most-studied techniques is generative design, especially in architecture at the conceptual design stage, which mimics nature's evolutionary approach to design. Generative design commonly uses four algorithms (Kasmarik 2010): shape grammars (SG), Lindenmayer systems (LS), cellular automata (CA), and genetic algorithms (GA). SG comprises a set of rules that can be applied consecutively to a geometrical construct to modify it via geometrical transformations (Sönmez 2018). Stiny and Mitchell (1978) presented ground-floor plan arrangements of Palladio villas using parametric SG. Downing and Flemming (1981) used parametric SG to express conventions governing space organization in bungalows. LS are a set of production rules that can be applied recursively through string rewriting. They differ from SG by operating on strings rather than directly on the shape itself and have been used to generate road networks and building forms (Müller et al. 2006). CA is a collection of cells on a grid of a specified shape that evolves according to a set of rules driven by the state of neighboring cells (Shalizi 2002). GA is metaheuristics inspired by the process of natural selection. They are search algorithms widely used to generate high-quality solutions to optimization problems, which are often described in terms of the variables to be optimized, design constraints, and objective function. Both architects and HVAC engineers use GA for design optimization. Tuhus-Dubrow and Krarti (2010) developed a simulation-optimization tool that utilized GA to optimize building shape and building envelope features. Palonen et al. (2009) used GA to solve a single-objective optimization problem aimed at minimizing the life-cycle cost (LCC) of a detached house. Parameters optimized in that study included the insulation thickness of the structure, U-value of the window, and type of heat recovery. Using GA, Wright and Farmani (2001) conducted simultaneous optimization of a building's fabric construction, HVAC system size, and supervisory control strategy for an HVAC system for a single air-conditioned zone. Asiedu et al. (2000) used GA to design an HVAC air duct system with minimum LCC. Besides using GA to optimize some aspects of HVAC design, Berquist et al. (2017) proposed a methodology to optimize design options during various stages of the HVAC design process using GA and developed a MATLAB program to generate zoning strategies for a given floor plan.

In recent years, AI has been explored for use in architectural design, especially in the conceptual stage, to help architects better evaluate possibilities and alternatives for design situations, use more effective design workflows and more productive design practices, and consequently, better plan for the spatial environment (Jrade and Jalaei 2013; Lin et al. 2021). Some studies combine AI with the HVAC domain, but most are related to system optimization to reduce energy consumption or life-cycle cost (LCC), improve indoor comfort, and conduct fault detection (Ahmad et al. 2016).

Machine learning (ML) is a subset of AI technology that has recently gained popularity. It is the science of getting computers to act without being explicitly programmed and to instead train themselves by using large amounts of data. In an interesting study about the implications of ML, Merrell et al. (2010) proposed a method for the automated generation of building layouts using a Bayesian network. It was trained on 120 building programs that were manually encoded (type, square footage, aspect ratio, adjacencies of rooms, global area, and footprint). Much of the research about HVAC system design uses ML to do analyses such as energy performance forecasting (Amasyali and El-Gohary 2018), fault diagnosis (Widodo and Yang 2007), indoor climate control (Grubinger et al. 2017), and passive design optimization (Chen and Yang 2017). However, research relating ML techniques to automated HVAC is scarce.

The duct layout design of an HVAC system is often labor-intensive and error-prone. Several concepts for auto-generating duct system designs have been proposed. Brahme et al. (2001) developed a method that combined heuristics and a shortest-path algorithm to design the air distribution system network and size its components automatically. Brès et al. (2017) proposed a method to generate models of potential HVAC distribution networks within buildings. However, the methods described were developed to build a more explicit and insightful building simulation model rather than to perform automated HVAC system design.

BIM refers to a combination or set of technologies and organizational solutions that are expected to increase inter-organizational and interdisciplinary collaboration in the construction industry and improve the productivity and quality of the design, construction, and maintenance of buildings (Miettinen and Paavola 2014). With the development of building informatization and the increasing use of BIM practices on projects, an HVAC-forward design process has been increasingly adopted. For example, an HVAC-forward design can be used to compare and select the design scheme, analyze feasibility, study the sensitivity of various measures, compare to standard building specifications, and obtain green building and LEED certification. In the design stages, the applications of BIM including analysis of the building's massing, daylight analysis, acoustic environment analysis, building energy simulation, electromechanical system design, pipe/duct collision inspection, etc. (Wong and Zhou 2015) In the operation and maintenance stages, the building model can also be used to study the control strategy and transformation measures, combine actual operational data, and execute a better predictive control strategy. Specifically, in terms of simplifying the design process of HVAC system based on BIM technology, BIM can realize the collaborative design of various architectural disciplines (Schlueter and Thesseling 2009), facilitate the comprehensive design of ducts/pipes and check the ducting/piping collision of the system (Wong and Fan 2013), etc. At the same time, it can also realize the simultaneous analysis of system layout, economic indicators and energy consumption indicators, etc. in order to optimize the design scheme. However, few studies have been conducted to integrate and form a framework for design automation or optimization methods of all stages in HVAC system design and make the design automatically.

BEM is a powerful, computerized method for investigating the performance of buildings and for evaluating the architectural and mechanical design. BEM can be created to help the designers evaluate multiple building design concepts involving various layouts, construction types, HVAC systems, fuel types and other basic architectural features at early stages (Petersen and Svendsen 2011). As the design phase progresses, parametric analyses support the designers to determine the relative impact of design modification to various building systems and subsystems, such as changing insulation values, HVAC system configuration, and control strategies. The design team could significantly benefit from BEM if it is applied at the design phase, the results of comparison of design alternatives are relatively accurate, because the energy simulation for different design alternatives are based on almost the same assumptions, and the common belief is that the relative differences in the simulation are reliable (Maile et al. 2007).

Green building XML (gbXML) and industry foundation classes (IFC) are data models that can be parsed by computers and are intended to facilitate interoperability between different BIM tools. Information needed for HVAC design, such as building geometry, room function, and envelope materials, can be obtained from these data models using design software. With the BIM-based BEM has become a prevalent topic in both research areas and software industries, some of the BIM-based BEM methods have already been developed and used in practice, including IFC-based methods and gbXML-based methods (Gao et al. 2019).

With the combination of AI techniques and BIM-based design, it is feasible that HVAC design could be completed largely by computers, leaving engineers more time to do creative work. In this paper, a conceptual framework of BIM-based HVAC design auto-generation is presented. The process described uses AI techniques that follow rule-based programs to mimic manual design procedures. And this method will be mainly applied to the design of HVAC systems in office buildings.

3 Methodology

HVAC design workload has been greatly reduced with the development and use of AEC (architecture, engineering, and construction) software. However, much repetitive work remains and needs to be performed manually, because these current design tools are not completely intelligent. For example, once an architectural layout changes, the HVAC system must be modified accordingly, requiring that tasks such as load calculation, equipment sizing, and duct layout be repeated. Thus, a truly intelligent tool is urgently needed to release engineers from this tedious work. This paper presents an outline of an automated HVAC design process, in hopes that this goal will be achieved soon with the help of computing power and machine intelligence development. A holistic view of the task decomposition of the automated design process is shown in Figure 2. There are four parts in the automated design process: model simplification, zoning and load calculation, system topology generation and equipment sizing, result and diagram generation, which are connected in a sequential structure. BIM-based architecture is the foundation of all the subsequent work. The routine

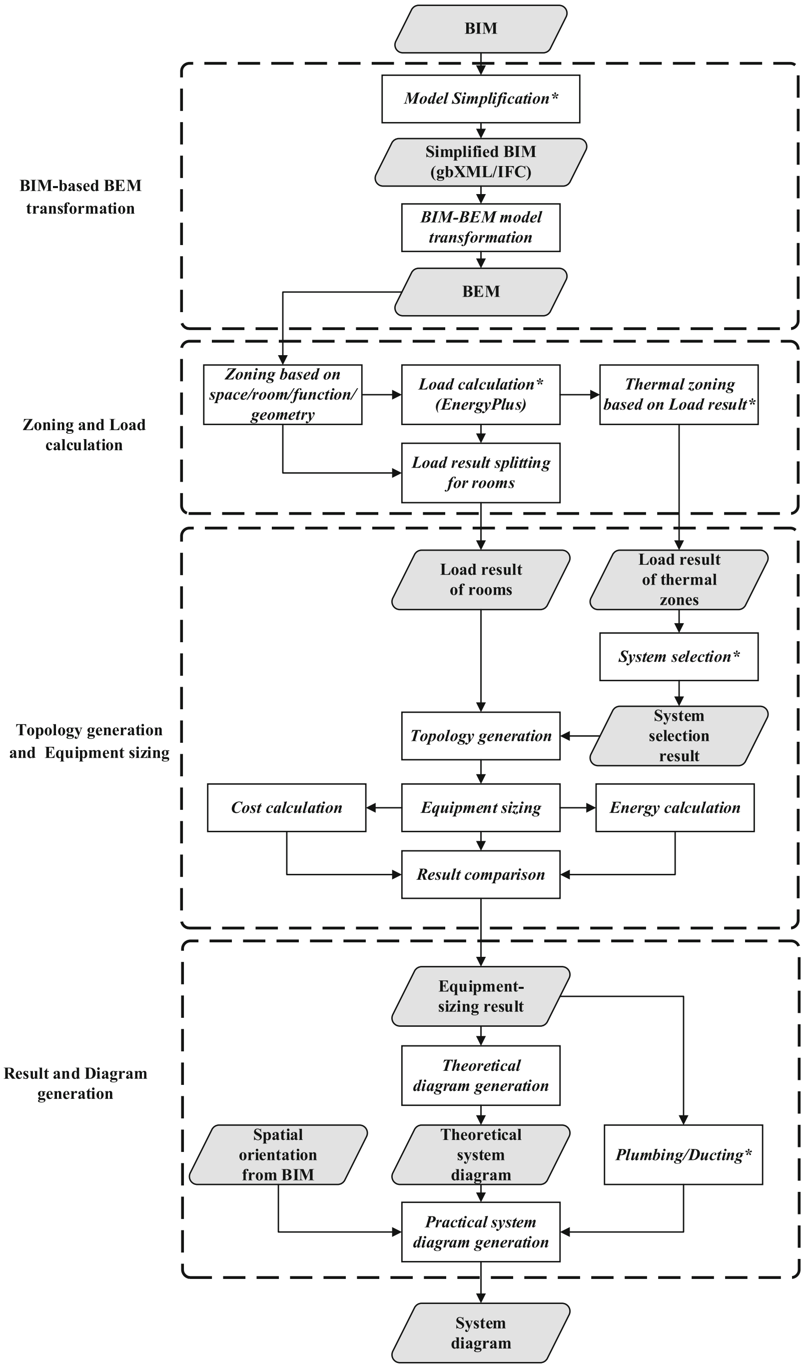


Fig. 2 A holistic view of an automated HVAC design process (Note: * represents a process that can be interfered with artificially)

uses rule-based AI technology to mimic the human-based design process step-by-step and contains several intelligent agents to solve each sub-problem.

3.1 BIM-based BEM transformation

Whether in the early stage of architectural design or the later stages of operation and maintenance control optimization, a BEM model is difficult to develop because of its nonlinear growth relationship with the calculation time. BIM is a more abundant model information base, so it is necessary to simplify the BIM information into a BEM model. In addition to the level of definition (LOD) and model view definition (MVD), the white-box physical model still needs to be simplified into a basic, transformed BEM model. To speed up computing time, it is necessary to simplify the BIM model by eliminating minor details such as stairs, doors, and ramps. BIM model transformation consists of two steps: one is to delete and filter the redundant information in the BIM model, and the other is to transform the simplified BIM model into a data model file containing the key building information. These two steps are done using a *BIM-based BEM transformation* agent which is shown in Figure 2. However, in the process of simplification, *External Intervention,* such as local fine-tuning of the generated building geometry model and other reasonable model modifications can be performed to influence the simplification results. The simplified model is used to calculate the building load, which is the foundation of HVAC design, using a gbXML file. Because compared to the IFC that aims to adopt a comprehensive and generic approach to represent an entire building project, the gbXML is mainly developed to facilitate data transformation from BIM to engineering analysis tools (especially for BEM tools) (Gao et al. 2019). The data which are needed to be retained in the gbXML file are shown in Figure 3.

Site location information is needed because it determines weather conditions. It is represented by *Location* in the gbXML file. The double-line wall model in the BIM model is transformed into a single-line model in the gbXML file. The geometric and structural information for the building wall is reflected in the *Surface* attribute of the gbXML file. Placement of walls requires the use of *CartesianPoint*, and each standard wall requires the inclusion of the material layer set definitions. The materials descriptions of other building envelope elements are of similar data structure. The building's room location and spatial function information are stored in the *Space* parameter of the gbXML file to provide all necessary information about the space as a functional area or the volume within a spatial structure. The occupant density, lighting and electric equipment power, and activity schedule are necessary for building load calculation and can be derived from the space functions according to the ASHRAE standard (ASHRAE 2016).

The simplification of the BIM model and the generation of the gbXML file can be secondarily developed using Autodesk-Revit, while the rest of the processes are based on Python programming. The gbXML text file is then processed into a BEM file. The transformation of the architectural geometry information involved in the process is limited by the completeness of the description information in the text file and the accuracy of the file transformation process,

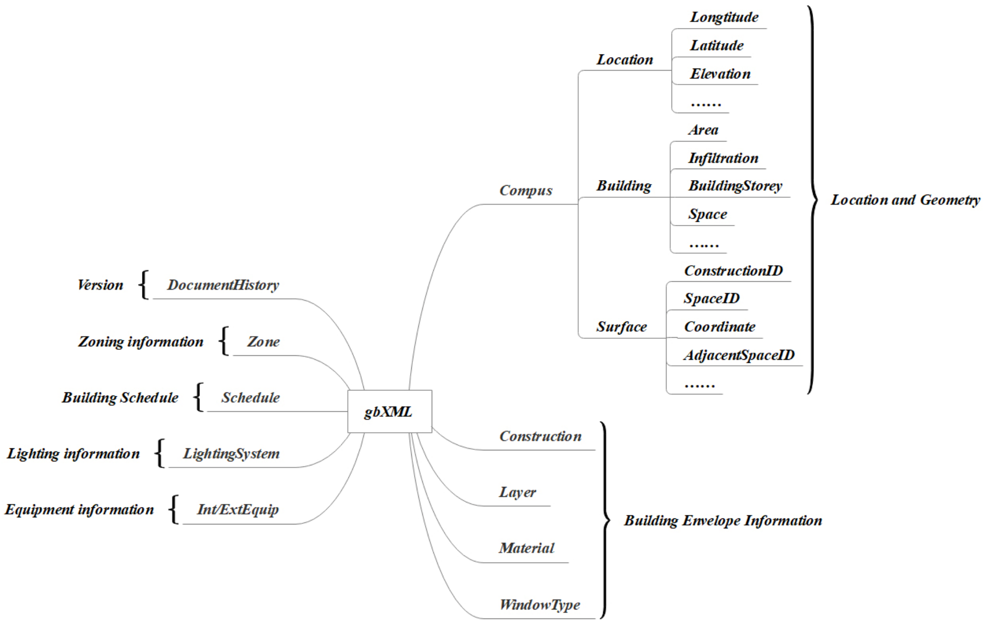


Fig. 3 Data required in the gbXML file

which often requires further checking. And this process is supplemented with information from a database that stores a large amount of historical building information and building energy models. The program can automatically match and supplement the file during the conversion process based on the input building location, room functions, geometric information and thermal parameters if available.

3.2 Zoning and load calculation

To generate a more precise load calculation for the indoor environment and provide better control of indoor thermal conditions in ventilated rooms, a detailed and computationally efficient model of the dynamic indoor temperature distributions is needed. The zonal model provides a simple and inexpensive approach for engineering design (Song et al. 2008). The basic idea of zoning is to divide the room air volume into several air zones, each of which is assumed to be perfectly mixed and is assigned one temperature or contaminant concentration. Autodesk-Revit uses a radiant time series (RTS) algorithm to calculate peak heating and cooling load, which is used to size plants (AUTODESK 2020). However, plant capacity may be oversized using this method because extreme weather conditions rarely appear. The yearly load profile is more suitable for selecting plant size and generating operational strategies. Therefore, this study uses EnergyPlus which is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), and managed by the National Renewable Energy Laboratory (NREL) as the load calculation engine for the transformed BEM model. A "zone" is defined as an area in a building with its own temperature control or load feature. It does not necessarily correspond to space in the original floor plan. For large buildings that contain hundreds of spaces, it is time-consuming to perform the calculations if each space is treated as a zone. Spaces of a similar type, load requirement, and orientation can be grouped as a zone, as shown in Figure 4. In this figure, the spaces filled with the same color can be grouped into one zone. This is a commonly used strategy for energy simulation modeling to reduce computing time.

In contrast, some spaces need to be properly split. A simple strategy is that for rooms with too large of a space or high connectivity, the outer boundary zone should be defined, at the least, according to the sunshine load area, referring to ASHRAE 90.1 appendix G, to establish an outer zone with a depth of 15 ft that better represents the local load of the space and prevents the underestimation of energy consumption. Splitting a large space is a geometric problem, so algorithms like *Clump Splitting* (Yeo et al. 1994), *Straight Skeleton* (Aichholzer et al. 1996), and *Hertel-Mehlhorn* can also be utilized.

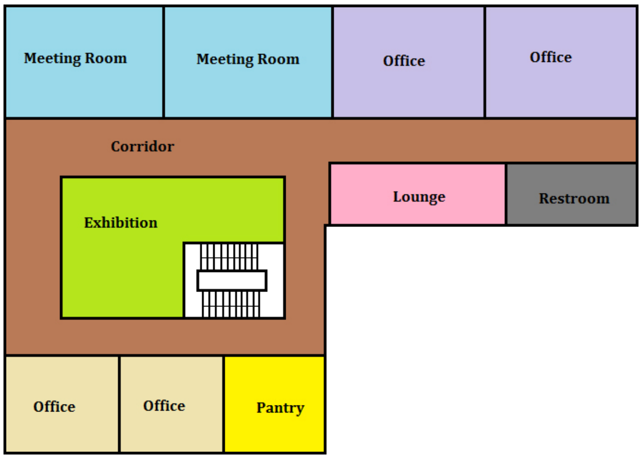


Fig. 4 Space gathering for zoning

Taking one floor of a museum as an example, as shown in Figure 5, the *Clump Splitting* algorithm can roughly split the polygons whose areas exceed a threshold value. It automatically identifies the bottleneck locations in the diagram to weaken the topological connectivity of a single thermal area. As shown in ① in Figure 5, the exhibition hall area is divided into three parts. The *Straight Skeleton* algorithm can be used to regress the exterior wall at the same rate to form the partition curve for the complex exterior area. As shown in ②, the outline of the outer area is indented based on the plane figure, and other thermal areas are avoided, as shown in ③. The *Hertel-Mehlhorn* algorithm can decompose the convex shape of polygons as shown in ④.

The *Zoning and Load calculation* agent contains a subagent called *Zoning based on space/room/function/ geometry*. The output file is a file with *.idf format that is ready for *Load calculation* using EnergyPlus. Eliminating the air-flow node model, which does not need to be considered in general energy analysis, can greatly improve the operational speed of the model. Combining spaces results in fewer indoor air nodes, which can significantly reduce computational complexity and improve the efficiency of iteration within a given error tolerance. In the *Load calculation* subagent, some *External Intervention* can be added, such as modifying the model's envelope material parameters and room schedules.

Using the cooling and heating load of each zone and the *Thermal zoning based on Load result* subagent, cluster

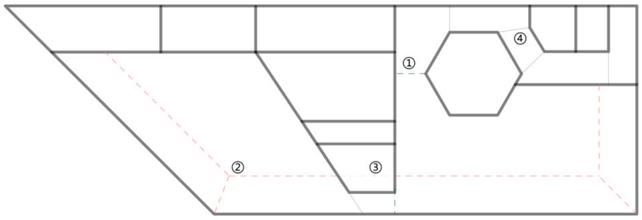


Fig. 5 Schematic diagram of the zoning of a museum

analysis is performed to identify the thermal zones for the HVAC systems. Based on the cluster results and the actual zone layout, the building rooms are divided into thermal zones such that the rooms with the same load characteristics are included in the same thermal zone.

It is necessary to merge the areas/rooms of the building into thermal zones for HVAC system based on the hourly load calculation results and building geometry. The basic idea is that if the hourly load calculation results of two areas/rooms present sufficient approximation in time series, then it is considered that they can be merged into the same HVAC system thermal zones. And the deviation of the parameter values of merged zones from the original zones is calculated as an indicator to evaluate the merit of the zoning results. Specifically, zoning mentioned here can be performed using two-dimensional clustering based on the characteristics of the amplitude and phase of the load calculation results of the rooms on the same floor in the building over a specific time window. The hierarchy of clusters needs to be searched for according to the distance of each area/room and the adjacency, in order to achieve the minimum number of clusters under the condition of meeting the minimum value of the deviation mentioned above. In addition, the designers can adjust the zoning results obtained from clustering to meet the design needs. The load results for these thermal zones are the basis of *System selection,* which is in the next agent.

The load calculation results are then utilized, along with the room information of the building, to get the load calculation results for different rooms using the *Load result splitting for rooms* subagent. This subagent maps the load results to each room of the building, based on the previous building geometric zone information and zone load calculation results, and the result is the basis for equipment sizing.

3.3 Topology generation and equipment sizing

System topology refers to the representation of the connections for the five loops in HVAC systems, which include the airside loop, chilled water loop, heat rejection loop, heating loop, and refrigeration loop. Taking the airside loop configuration as an example, the thermally similar spaces are usually contained in one system. Additionally, space adjacency is another important issue requiring consideration. If two offices are on the opposite sides of the building, the routing of the ductwork would be almost impossible to construct. Through the auto-zoning process described above, rooms with closely spaced locations and similar functions and load requirements are grouped automatically for system design and this is realized in previous agent. It should be noted that thermal zoning strategies are different for different system types. For example, offices having similar load features may be combined for a variable air volume (VAV) system but should be split for a fan coil system. The preliminary selection of the system occurs based on the results of the completed thermal zone analyses. For analysis purposes, this paper specifies the most common system for the chilled water loop, which uses a chiller and boiler for the cooling/heating source. As is shown in Table 1, there are different types of loop configurations, and each of them has advantages and disadvantages. The traditional design process for both airside loop and chilled water loop configurations is highly dependent on design specifications and the experience of engineers to determine the most suitable configuration for a specific project. Thus, *External Intervention* can be used to influence the system configuration. Additionally, various accessories, such as fittings, water distributors and collectors, valves, filters, thermometers, and pressure gauges should be included in the duct/pipe systems and configured in these loops to ensure normal operation.

Because plant size is highly dependent on the loop configuration, the heating and cooling source plants can be sized after the HVAC loops have been determined. In practice, engineers typically use the peak load to define plant total capacity and choose several evenly sized plants in consideration of the partial load condition. However, this strategy is not the optimum (Fu 2016). It is essentially a design problem based on the configuration of a HVAC system with a known topology and should be a complex multilevel, nonlinear convex optimization problem with different types of variables (Wright et al. 2008). Wight and Zhang (2005) represent the selection variables of the system components and the system structure characteristics by different variable types so that the selection and design process can be represented by an optimization model. In this study, we made a partial simplification of this optimization problem. Plant sizing is conducted based on the annual load profile instead of just peak load. The annual load-variation characteristics of the buildings are used to determine the optimum configuration for the heating and cooling source plants, with the constraints set to be unmet hours and partial load rate which considering the year-round operating characteristics of the plants. The optimization variables are plant quantity, each plant's capacity, and plant location (for high-rise buildings). Plant sizing algorithms are realized in agent *Equipment sizing* and the detailed algorithm flow which is based on selection manual and ASHRAE standard of HVAC system equipment will not be described here.

The HVAC distribution system conveys the heating or cooling medium from the generation site to the terminal and is indispensable in the loops. The current distribution

Table 1 Different types of water-side systems

Type	Description	Advantages	Disadvantages
Reverse return system	Supply water and return water have the same flow direction. Supply pipe and return pipe have the same hydraulic length.	Easy to maintain hydraulic equilibrium.	High initial investment cost. High pressure drop.
Direct return system	Supply water and return water have reverse flow directions. Supply pipe and return pipe have different hydraulic length.	Low initial investment cost. Low pressure drop.	Hard to maintain hydraulic equilibrium, especially in a large system.
Two-pipe system	Cooling and heating water are supplied and returned through one system.	Low initial investment cost. Occupies less space and is a simple structure.	Impossible to meet the heating and cooling demands simultaneously.
Three-pipe system	Cooling and heating supply water uses separate systems, while the return water shares one single system.	Able to meet the heating and cooling demands simultaneously. Medium initial investment cost.	Energy loss due to heating and cooling return water comingling.
Four-pipe system	Both supply and return water use separate systems for cooling and heating.	Able to meet the heating and cooling demand simultaneously. No energy loss due to heating and cooling water comingling.	High initial investment cost. A complicated structure that occupies more space.
Constant flow system	Water flow rate constant, and the load changes with water temperature.	Simple structure and control logic.	High transmission energy consumption.
Variable flow system	The water temperature stays constant, and the load changes with the water flow rate.	Energy-efficient. Smaller duct size and pump capacity.	Hard to operate.
Primary pump system	The supply side and demand side share one set of pumps.	Simple structure. Low initial cost.	Not suitable for high-rise buildings or those with sub-blocks having great disparity in their pressure drops.
Primary-secondary/multiple pump system	Supply side and demand side have exclusive pumps.	Energy-efficient for high-rise buildings or those with sub-blocks having great disparity in their pressure drops.	Large pump capacity. High initial investment. Complicated structure and hard to operate.

system design process is extremely time-consuming and is the type of work at which computers are adept. Brahme et al. (2001) developed an agent for distribution system design in the early design stage. It uses heuristic rules and a shortest-path algorithm to design the distribution system. “Heuristic algorithm” refers to the common practice of network design used by HVAC engineers. For example, to maintain hydraulic equilibrium, the network should be symmetrically assigned. The shortest-path algorithm is used to connect two nodes at each step and can avoid obstructions during path generation (Horowitz and Anderson-Freed 2007). This study utilizes this algorithm with some modifications because it assumed that all spaces in a zone are contiguous and that the system type has been assigned.

After load calculation and topology generation are completed, the equipment listed in Table 2 can be sized according to load requirements and pressure drops.

System configuration is a decision-making and searching process performed by the *Result comparison* subagent using a finite solution pool that is the collection of results obtained from configuring the system loops based on the previously determined thermal zoning results. Building information and user preference are inputs for this decision-making. Heuristic knowledge about common practices, such as element connection and accessory selection and allocation, is also necessary. The knowledge required to evaluate a system selection decision includes, but is not limited to, energy consumption and cost, which includes the initial investment and maintenance costs, therefore, two evaluation modules are also included in this automated design framework

Table 2 List of equipment for sizing

Equipment type	Sizing variable	Reference
Fan	Pressure	Pressure drop of the air system
	Flow rate	Load and temperature difference
Cooling coil	Cooling capacity	Load
Heating coil	Heating capacity	Load
Pump	Pressure	Pressure drop of the air system
	Flow rate	Load and temperature difference
Cooling tower	Flow rate	Load and temperature difference
Chiller	Cooling capacity	See Section 3.3
Boiler	Heating capacity	See Section 3.3

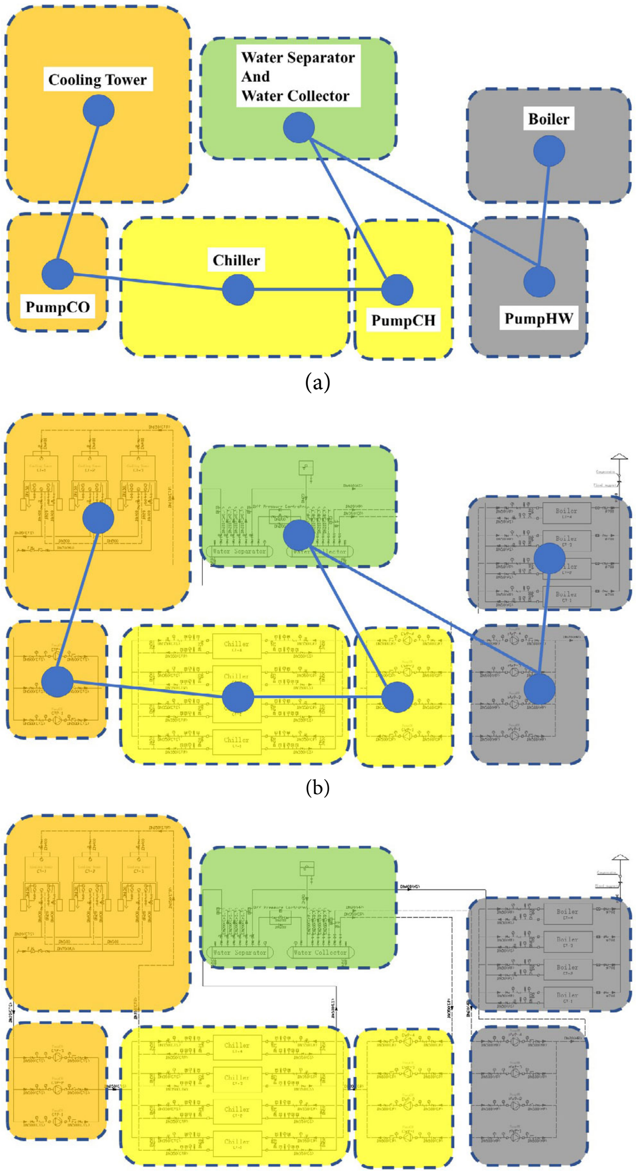
as *Cost calculation* and *Energy calculation* subagents. The system configuration results are produced in Json format which is one of the lightweight data interchange formats.

3.4 Result and diagram generation

Based on the outputs of *Topology generation and Equipment sizing* agent, the design results of HVAC system based on specific project can be easily obtained. And the design results can be output in any file format. In addition, it is necessary to produce 3D models or 2D diagrams to illustrate the automated HVAC design results. Creating a detailed and practical HVAC construction diagram for HVAC engineering is an extremely complex process. At present, detailed construction design drawings for an HVAC system cannot be automatically generated by technical means. Duct and pipe design must fully consider the specific spatial geometry inside the building and requires extra attention because clashes with other systems frequently occur.

However, in the early stages of HVAC schematic design, the generation of a theoretical HVAC scheme diagram is relatively simple, and it is expected that automated drawing tools can replace this work. Once the preliminary system topology design is generated and the equipment selected, the system diagram can be drawn. Taking the water system schematic as an example, each loop corresponding to the selection result can be connected based on the components of the loop. Similarly, each component can be connected based on the equipment of the component. For example, the cooling water loop contains two components, the cooling tower, which includes the cooling towers, pumps, sensors, and valves, and the cooling source components which include the chillers, pumps, sensors, and valves. The general process of system diagram generation is as shown in Figure 6.

Firstly, the topological structure is abstracted and simplified according to system topology, and the input parameters are summarized hierarchically. Next, the layout of the loop topology is performed, as shown in Figure 6(a). The connection interfaces of the components are drawn according to the properties of the components in the loop, and the connection between components is drawn based on the relationship between the components. Next, based on the selection results, the topological structure and connection relationships of the internal equipment of the components are drawn, as shown in Figure 6(b). Finally, the distribution devices and additional devices in the loop are drawn, and the final diagram is as shown in Figure 6(c). The output file format of this agent is *.dxf which is a CAD data file format developed by Autodesk for CAD data exchange between AutoCAD and other software. The output files here are editable graphic files that allow designers to adjust to their preferences and meet their requirements.



(a)

(b)

(c)

Fig. 6 System diagram generation process

4 Experimental study

An example office building was utilized to evaluate the proposed process and demonstrate the automated design procedure more explicitly. The architectural BIM model shown in Figure 7 was developed using Auto-Revit. The 4750 m^2 three-floor building is in Shanghai, China of hot summer and cold winter.

4.1 BIM-based BEM transformation

The typical sequence of building design is architectural design, structural design, and building service design. The automated HVAC design tool receives a BIM model with

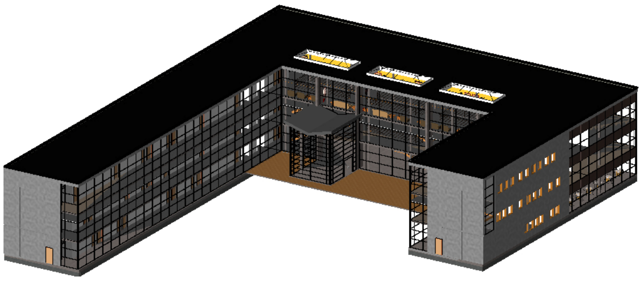


Fig. 7 BIM model of example building

detailed information about geometry and accessories, such as external ornaments, doors, interior windows, stairs, desks, and sanitary fixtures. The BIM model of the example building is simplified by deleting the elements of the model except for the wall, ground, door, window, floor, roof, room, and room marks, and the space information is corrected in the original BIM model. The 3D appearance of the BIM model after this simplification is shown in Figure 8.

Subsequently, Auto-Revit exports a gbXML format file corresponding to the simplified BIM model, in which the building information of the simplified model is saved. With the assistance of model visualization tools, the 3D information about the buildings contained in the gbXML file can be visualized as shown in Figure 9.

The gbXML text file is processed and converted to a BEM file, with the help of a conversion tool we developed, resulting in the BEM file for use in the next step. With the assistance of model visualization tools, the 3D information about the buildings contained in the *.idf format file can be visualized as shown in Figure 10.

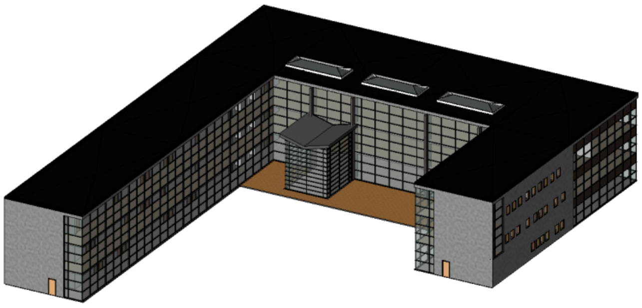


Fig. 8 Simplified building model

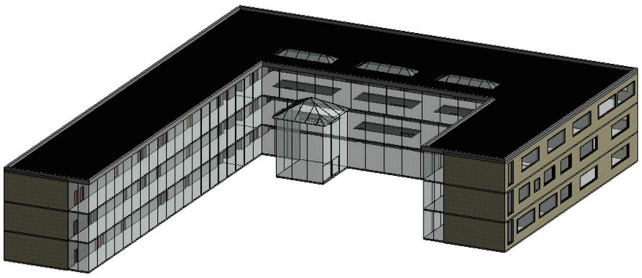


Fig. 9 Simplified building model (gbXML format)

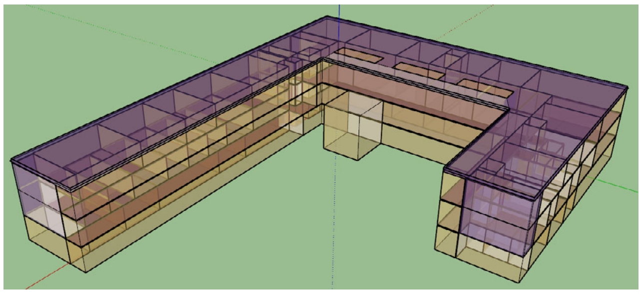


Fig. 10 Simplified building model (*.idf format)

4.2 Zoning and load calculation

Using the simplified BEM building information input file, the *Zoning based on space/room/function/geometry* subagent provides the zoning results. As an example, the results for the first floor are shown in Figure 11.

The *.idf format file is utilized by the EnergyPlus engine for load calculation. Because there are relatively few rooms in the building, this example designated each room as a zone for performing the load calculation and analysis and determined the load calculation results for each zone (room). The output is an hourly load profile in comma-delimited (*.csv) format, the data for which is graphed in Figure 12. The calculation results show that the peak cooling load of the entire building is 526.07 kW, the cooling load per unit air conditioning area is 118.02 W/m^2, the peak thermal load of the whole building is 365.61 kW, and the thermal load per unit air conditioning area is 82.02 W/m^2.

The processing of the *Thermal zoning based on Load result* subagent yields the thermal zoning results shown in Figure 13. It can be observed that the load hierarchical clustering processing combined zones 4 and 5 because of their similar load characteristics from their hourly load calculation results.

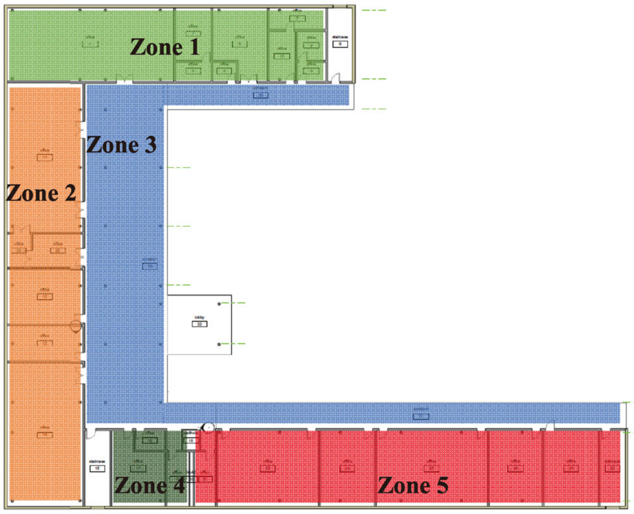


Fig. 11 Result of *Zoning based on space/room/function/geometry*

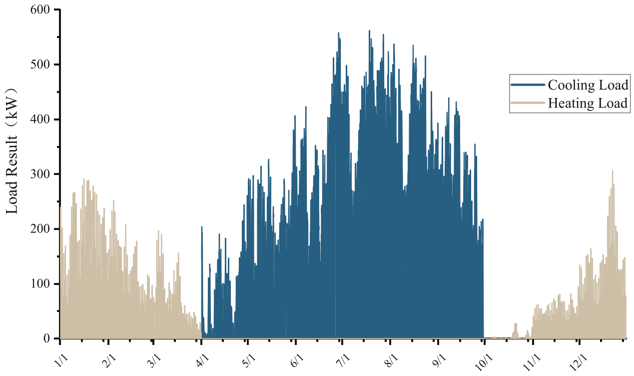


Fig. 12 Load calculation result

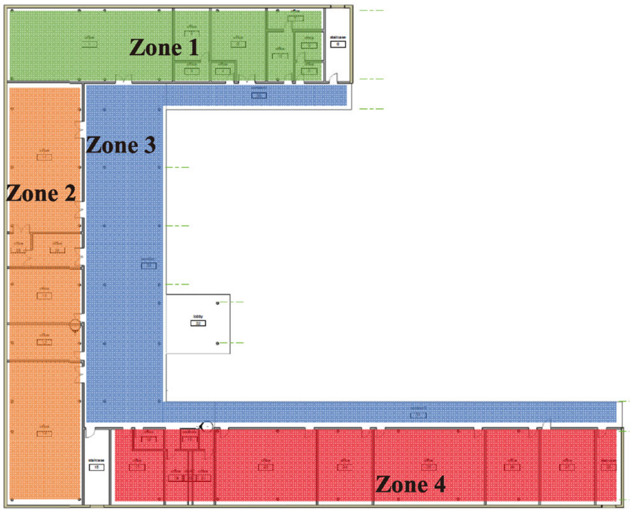


Fig. 13 Output of *Thermal zoning based on Load result* subagent

4.3 Topology generation and equipment sizing

In this step, an air source heat pump was chosen as the cooling/heating source, and fan coil units with a dedicated outdoor air system were selected as the terminal system for this building. The topologies of the system loops are shown in Table 3.

After the system type is selected, the equipment list for auto-sizing can be generated, as shown in Table 4.

In this study, a sample database containing several equipment options was developed. The total cooling/heating load (sensible heat load) and total latent heat load of the building are used to determine the quantities and models of the chilling equipment after composition from the database. The selection results are shown in Table 5.

Based on the nominal water flow of the unit and the water-lift of the system, the estimated requirements for the water pump(s) can be obtained and are shown in Table 6.

The fresh-air cooling load and volume of fresh air are utilized for the selection of the fresh-air handling units. The result is shown in Table 7.

The load calculation results for each room, combined with the supply and return air temperature differences in the room, determine the model and quantity of terminal equipment required in the room. In this example, a fan coil unit is used as terminal equipment and the selection results are shown in Table 8.

The selection results for other accessories are not described in this paper. The next steps are determining the general pipeline direction, based upon the internal structure

Table 3 Topology of system loops

Loops	Component 1	Component 2	Component 3	Component 4
HVAC system loop	Air source heat pump unit	Water pump	Water separator	Water collector
Zone loop	Terminal of fan coil units	Fresh air unit	Water circuit network	Air circuit network

Table 4 Equipment list for auto-sizing

Cold and heat source	Valves and sensors	Fresh air system
Air source heat pump unit	Ball valve	Fresh air grille
Water separator	Shut-off valve	Fresh air valve
Water collector	Sluice valve	Air filter
Electronic decontaminator	Manual control valve	Supply air fan
Softened water unit	Quick-release valve	Air duct
Softened water box	Balance valve	Short supply air pipe
Feedwater pump	Differential pressure switch	Anechoic chamber
Condensate tank	Electric two-way valve	Air volume regulator
Condensate pump	Thermometer	Air valve controller
Steam-water heat exchanger	Check valve	Diffuser
Water pipe	Flowmeter	

Table 5 Selection parameters of air source heat pump

No.	Manufacturer	Type	Nominal cooling capacity (kW)	Nominal heating capacity (kW)	Electric power of cooling (kW)	Electric power of heating (kW)
30RQ202G	Carrier	Scroll	197	218	64.5	63.7
30RQ412G	Carrier	Scroll	378	432	128.2	128

Table 6 Water pump selection list

No.	Type	Nominal flow (m^3/h)	Water-lift (kPa)	Power (kW)	Pipe diameter (mm)
KQW80/185-11/2	Horizontal	56.4	392	11	80
KQW80/185-11/2	Horizontal	56.4	392	11	80
KQW80/185-11/2	Horizontal	56.4	392	11	80

Table 7 Fresh air handling units' selection list (part)

No.	Type	Air volume rate (m^3/h)	Cooling capacity (kW)	Heating capacity (kW)	Water flow rate (m^3/h)
DBFP150	Hoisting	15000	198.2	206.8	27.11
DBFP150	Hoisting	15000	198.2	206.8	27.11

Table 8 Terminal equipment selection list (part)

Room No.	No.	Air volume rate (m^3/h)	Cooling capacity (W)	Heating capacity (W)	Power (W)	Water flow rate (m^3/h)	Number
1F:28 OFFICE	FP-34	255	1440	2160	37	0.31	1
2F:65 OFFICE	FP-51	383	2160	3240	52	0.46	2

of the building, performing the hydraulic calculations, designing the pipe diameter of each section, and generating information about the connection relationship between the pipeline and the equipment.

4.4 Result and diagram generation

In this section, we used the agent we developed which is called *Theoretical diagram generation* to generate the water system schematic with the algorithm in Section 3.4. This agent is designed by us based on Python programming. And the water system schematic of cooling and heating source designed for experimental building is shown in Figure 14.

After testing the procedure, its results and issues were analyzed, and it was determined that the results of each automated design project in this design example yielded the expected results. Therefore, the great degree of automated and effective design results produced by this design process can be considered a successful demonstration of automated design.

4.5 Productivity improvement

This study investigates the design process, methods, and difficulties of traditional HVAC system design, and concludes the pains of current HVAC system design. The survey covers 100 designers and engineers with short-term or long-term experience in HVAC system, mainly in form of questionnaire survey and interview. The following are parts of the result.

The survey results show that, at present, to realize the HVAC system design of a complex building with a building area of 100000 m^2, it needs to invest at least 135 people per day. And with the increase of the building area and the complexity of the building geometry, the workload required to complete the air conditioning system design will gradually increase.

According to the survey results, it is found that the average modification times of each single item in the HVAC system design work of a 50000 m^2 office building completed by the HVAC system design practitioners with more than 5 years of working experience are shown in Figure 15(a). It shows that the average modification times are more than 2 times, and the drawing work needs the most modification times. The average working time of these engineers of completing each individual project is shown in Figure 15(b), in which the drawing time is the longest, with an average of 161 hours, accounting for 37% of the total project work time. Correspondingly, the survey found that the average modification times of each single item of the HVAC system design work content of a 50000 m^2 office building completed by the HVAC system design practitioners with less than 5 years of working experience are shown in Figure 16(a).

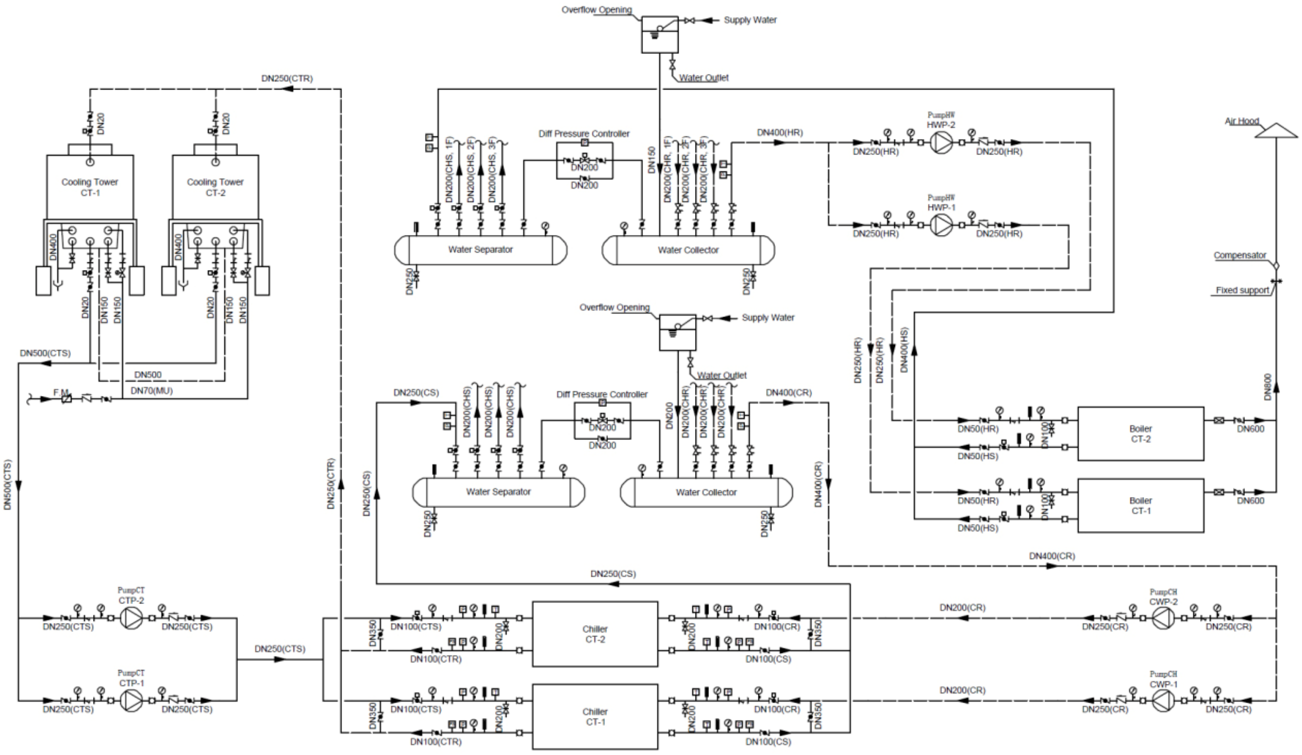
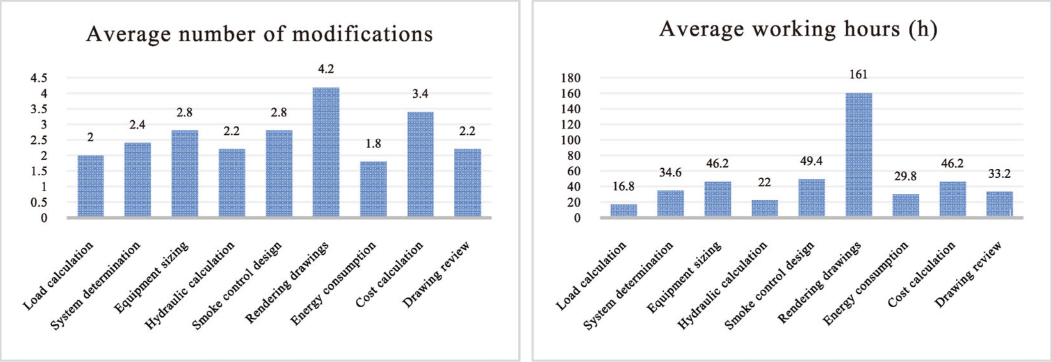
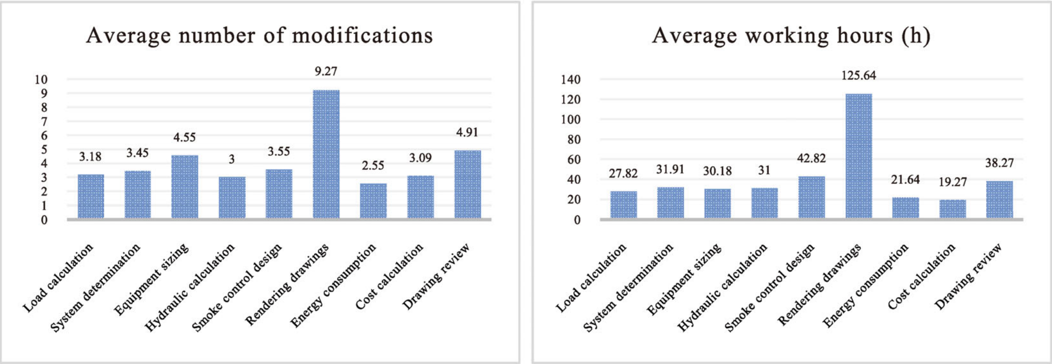


Fig. 14 Water system schematic of cooling and heating source



(a) (b)

Fig. 15 Survey results of practitioners with more than 5 years of working experience



(a) (b)

Fig. 16 Results of practitioners with less than 5 years of working experience

It shows that the average modification times are more than 3 times, and the drawing work also needs the most modification times. The average input time of these engineers to complete each individual project is shown in Figure 16(b), in which the drawing time is the longest, with an average of 125.64 hours, accounting for 34% of the total project finishing time.

Based on the automatic design process framework of HVAC system proposed in this study, we connect the four agents of the framework through computer programs, and finally complete the whole automatic design process of the experimental case. The automatic design program based on the framework of this project can complete the whole process of the experimental case from BIM to BEM transformation to the final generation of HVAC water system schematic diagram in 40 minutes. While it takes about 23.37 working hours to estimate the same process based on the results of questionnaire survey. It is obvious that automatic process framework is feasible, compared with the traditional design process can effectively shorten the design time and improve the productivity.

5 Discussion

Since Carrier invented the first centrifugal chiller in 1922, the use of large-scale air conditioning systems has expanded throughout the world. New HVAC technologies emerge continually, and nearly all large commercial buildings require HVAC design engineers to manually design the built-up systems. These design engineers perform substantial amounts of tedious and repetitive work.

Many methods and tools have been developed and constructed by applying AI techniques to the design process. However, most of these tools are only applied for some specific aspects of the design, and some tools and methods are not integrated into the traditional design practice and finally neglected (Sha et al. 2019). The reason is that using mathematical methods to describe and define design problems requires high skills and experience, which are often beyond the ability of HVAC engineers. In addition, the conventional design is carried out in 2D graphics, and the design information must be extracted manually. Extracting information itself is a time-consuming and laborious process. These are the reasons why the current AI techniques are limited to specific research areas and not widely used in HVAC system design practice.

In recent years, building information modelling is widely used in architectural design. As a digital representation of building features and functions, BIM can be extracted, exchanged, or networked to support decision making regarding a building or other built assets, and play an important role in the whole life cycle of buildings. This kind of information is often stored in some standard information files, such as gbXML and IFC, which can make it easy for computers to obtain information.

The design of traditional HVAC system is a complex process, including many steps. And the design cannot be simplified as a single mathematical problem or solved by a single method or algorithm. In this study, the complex design process is divided into four agents, and each agent is simplified based on certain assumptions. To our knowledge, this study is the first time that the traditional design process is automated connected by the current AI techniques and artificial design methods. The framework in this paper can enhance the digitization of HVAC system design, which can facilitate the inclusion of more AI algorithms in the future. The machine-generated design results are somehow unable to meet the requirements of the actual design project, so the results generated based on this framework still need to be reasonably modified by designers based on the actual engineering requirements. In the meantime, a simple office building design case is used to verify the automation design framework proposed in this paper. The experimental results show that compared with the traditional design process, the automatic HVAC system design based on this framework can greatly reduce the repetitive work of designers, shorten the design time, and improve the design productivity.

6 Conclusions and further work

This paper presented a framework for an automated HVAC system design tool based on multiple agents that mimic human-based design practices. The proposed methods for each step were described, and then a simple three-floor office building was used as an example to prove that using software to automate such a procedure is feasible. This paper described a basic framework for an automated HVAC design procedure. It is envisioned that, eventually, architects will perform HVAC system design themselves, in parallel with other disciplines' engineers. In the meantime, we are developing software based on Python interpreter to facilitate these procedures, which will significantly reduce the amount of HVAC engineering time required.

The BIM-based HVAC system design workflow proposed in this paper is an attempt to integrate and apply the current fragmented building information to the forward design of HVAC systems. It will be served as the information source of the BIM-based life cycle information integration system of buildings, which will improve the efficiency of HVAC system forward design while reducing its cost and threshold.

However, the automatic design process proposed in this study is a bit far from complete automation and still requires manual intervention. Based on the existing technical methods, it can initially realize the automatic calculation, design and result generation of simple office buildings. For buildings with complex or special geometry, it is often impossible to use the existing design methods to get the ideal design results. Firstly, BIM-based BEM transformation method is not mature, and there is no unified standard for current BIM model construction. The LOD and MVD of models for different design stages and design purposes are not the same. Therefore, it is often impossible to extract room or space boundaries from complex building models and transform them to BEM. This leads to no way to find a general BIM based method for BEM automatic transformation. Secondly, there is no completely feasible solution for the complex spatial layout and geometric structure of the building geometric zoning and HVAC system zoning. In addition, the increase of space complexity will lead to the increase of plumbing and ducting complexity of HVAC system, and the current CAD methods of HVAC system pipes/ducts are mostly semi-automatic design methods that need human intervention.

The framework proposed in this study is a sequential structure, but the design problems for specific projects often need repeated iteration and optimization to obtain better design results. Usually, the design optimization of HVAC system is based on the following key optimization objectives: initial investment and operation cost, operation energy consumption, indoor thermal comfort, and indoor air quality. Although the *system topology generation* agent has been involved in the optimization of system selection form and preliminary selection results, there is still a lack of more in-depth research on the optimization of more complex transmission and distribution system.

The main subject of this study is the optimization of HVAC system design process in office buildings and does not involve other subsystems or subspecialties in architectural design, which is also one of the limitations of this study. In the future, we can increase the research on the design of all building subsystems on the basis of BIM-based automatic design method of different building subsystems. This research progress will be presented in subsequent papers.

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